DESIGNING FUNCTIONAL HABITAT USING WILDLIFE HABITAT RELATIONSHIPS: A MISSING CURRICULAR CONCEPT IN LANDSCAPE ARCHITECTURE EDUCATION

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1. ABSTRACT
The purpose of this paper is to describe wildlife habitat relationships (WHR) and its basis for use in landscape architecture and habitat design. An 'ecological greenway' design process, within a landscape planning and design studio context, provides examples of student work using WHR models in three river case studies in the Central Valley, California. WHR modeling is species-specific life history information that links vegetation communities and their structure to individual wildlife species suitability models. Without incorporating WHR models for focal species in a design process to predict functionality for wildlife species of concern, it is unlikely a landscape will effectively function for them. None of the major textbooks in landscape architecture have an adequate description of WHR models despite their utility in ecological design. Students implemented an integrated dual-track design process, one track focused on natural systems and the other on cultural systems. For these exercises emphasis was placed on natural systems conservation planning and design using a set of focal species. To design habitat areas for each focal species, a California-specific WHR system was utilized. Students created a GIS database for each case study by collecting a variety of data layers including land use, land cover, roads, 100-year floodplain, and soils. Techniques utilizing GIS, CAD, and illustration software were combined to create site analyses and phased master plans for each river system. GIS was used effectively to communicate phasing in an animated sequence. WHR is a vital concept in ecological design and should be included in landscape architecture curricula.

1.1 Key Words
Ecological greenway; wildlife habitat relationships; habitat design; migration corridor; rivers
2 INTRODUCTION

Ensuring that landscapes and greenways are intentionally designed to serve ecological functions and meet the habitat requirements of specific wildlife species is the focus of this paper. A very important tool for greenway and ecological designers is the utilization of wildlife habitat relationships (WHR) models. WHR modeling is species-specific life history information contained in a database that links the composition and structure of vegetation communities to individual wildlife species suitability models (Beck & Suring, 2009; Morrison, Marcot, & Mannan, 2012). Without considering or incorporating WHR models into a design process to "build-in" or "predict" functionality for wildlife species of concern (e.g. threatened or endangered), it is unlikely a landscape or greenway will effectively function for them. Unfortunately, this basic method to conceptualize and design functional habitat is missing from nearly all major textbooks in landscape architecture and environmental planning. The WHR literature remains primarily in highly specialized articles and books on wildlife habitat analysis. However, a paradox exists because some literature in landscape architecture (such as Ndubisi, 2002; Verboom & Pouwels, 2004) actually address advanced uses of WHR models in the context of metapopulation analysis (i.e., modeling population viability). It appears these advanced methods (e.g., using LARCH or LANDEP) tend to be used more by ecological scientists and less by environmental designers and planners. Thus, there remains an important knowledge gap at the undergraduate (introductory) level of the basic concepts of WHR and how it can be used to design functional wildlife habitat. This issue is further addressed in the Discussion.

The objectives of this paper are: (1) to describe the basic concept of WHR and how it can be used in habitat evaluation, ecological design, conservation planning, and greenway design in a studio course context; (2) to describe a planning and design process and show some student work products from a series of undergraduate greenway design studio courses using WHR methods on three California river systems; and (3) to review and critique literature in landscape architecture (including prominent educational textbooks, book chapters, and journal articles) regarding WHR concepts and methods.

2.1 What is WHR, how is it measured, and how is it used?

Wildlife habitat is a species-specific concept, meaning habitat types — such as vegetation communities and other land cover — have different suitability values for each species (Beck & Suring, 2009; Verboom & Pouwels, 2004). WHR models describe the ecological needs of individual species by breaking down habitat into various life history functional units (or "life requisites") such as (1) feeding habitat, (2) cover habitat, and (3) reproductive habitat (Cooperrider, 1986). WHR is an extension of ecological niche theory and is sometimes referred to as "resource selection functions" (Noss, O'Connell, & Murphey, 1997). Habitat is often represented as a land cover (choropleth) map typically using a floristically coarse classification system of vegetation communities. Each of the three life requisite variables are separately scored for suitability (on a scale from zero to 1.0; see section 2.2 below for more detail) and the three scores can then be averaged or weighted (mathematically combined) into a single habitat suitability index (HSI) score. There are many metrics to combine the separate habitat scores (see Cooperrider 1986, p. 767), but two widely used metrics are the arithmetic and geometric means (statistical averages) as shown below:

\[ HSI = \frac{R + C + F}{3} \]  
\[ HSI = \sqrt[3]{R \times C \times F} \]

where \( HSI \) is the habitat suitability index for a particular wildlife species at a site and \( R \) is reproduction habitat, \( C \) is cover habitat, and \( F \) is feeding habitat (CDFW, 2014a). Equation 2 is a more conservative metric because if any of the life requisite variables is rated as zero then the entire HSI score is zero. It should be noted that the suitability scores (or ratings) of each life requisite habitat type are usually designated by species experts or by scientific studies of habitat preference; they are empirical estimates based on the best available information.

The following example illustrates this overall approach. If a species at a particular site has feeding habitat rated as 1.0 (excellent feeding habitat), cover habitat rated as 0.66 (medium), and the site lacks any reproductive habitat (i.e., reproduction = 0; or unsuitable), then its arithmetic mean is 0.55 and its geometric mean is zero. If population persistence at the site is a management imperative then the latter
metric (Equation 2) is more appropriate because it explicitly requires that all three habitat types are present and suitable, including reproductive habitat.

Another important aspect of WHR models is the presence of certain 'habitat elements' or 'habitat components' at a site that are essential for a species survival and persistence (Cooperrider, 1986, Table 1, p. 760; CDFW, 2014a, p. 13-14). Habitat elements can be 'living' or 'dead' resources, for example snags for late-seral cavity nesting birds, or rock piles for most reptiles, or small rodents as prey for raptors. Such habitat elements may not be mapped easily using GIS land cover data and therefore its presence is often confirmed by field visits to the site being evaluated.

WHR models can be used for many purposes. Often they are used to predict which wildlife species could potentially be present at a site, a method commonly employed in habitat conservation plans (HCPs; implemented under the federal Endangered Species Act; see Noss et al., 1997). Another application for WHR models is for estimating impacts in environmental impact statements (EISs; implemented under the federal National Environmental Policy Act) by predicting the potential loss of habitat and species associated with those habitats due to urban development or timber harvest. A third application, which is the focus of this paper, is for designing functional habitat (using patch composition, structure, and habitat elements) for selected focal species or species of special concern. WHR models can also be used to infer ecological processes such as seasonal migration and juvenile dispersal for wildlife species with those needs. Maintaining processes such as these is a great challenge in nature conservation planning. For wide ranging generalist species such as most ungulates, WHR models can be used to design contiguous habitats, commonly referred to as "wildlife corridors" where habitat connectivity is essential. Functional connectivity (as opposed to structural connectivity) means that the corridor is composed of habitat types that a species has been observed using to migrate, thus "connectivity is both species- and landscape-specific" (Noss, 2006, p. 71 citing Bennett, 1999).

A common dilemma in greenway planning is justifying the areal width of the park's physical alignment. In the case studies presented below, greenway width is determined by the ecological function of a seasonal migration corridor for a wide ranging ungulate species and habitat for endangered species. Suitable habitat types were identified using a WHR system designed for California wildlife species. Spatial dimensions and configuration of the migration corridor were derived from a species-specific spatial study of migration (see section 3.2 below for further discussion). It is important to note that most WHR systems (databases) do not yet have a spatial component for determining minimum patch sizes or corridor configuration parameters, though these will likely be developed in the future. Another criterion for determining greenway width on a river system is using flood frequency, in particular, the boundary of the 100-year recurrence interval (see Greco & Larsen, 2014).

2.2 WHR systems

There are numerous WHR modeling systems that have been developed in the U.S. and worldwide. For example see the Oregon and Washington state WHR system (Johnson & O'Neil, 2001). This paper mainly focuses on the California Wildlife Habitat Relationships (CWHR) system that was first developed in the 1980s to describe habitat use by all terrestrial vertebrates in the state (Mayer & Laudenslayer, 1988). Currently the database system has 712 species represented as WHR models including all birds, mammals, reptiles, and amphibians. The database is a stand-alone program for Windows-based PC computers and is now free and available to the public though the California Department of Fish and Wildlife website along with multiple support documents (see https://www.dfg.ca.gov/biogeodata/cwhr/). The current version (CWHR v9.0) was recently released and runs on Windows 7 (and above) operating systems and accommodates 64-bit computing (CDFW & CIWTG, 2014b).

The CWHR system classifies habitats into seven tables of broad categories of major habitat types: (1) trees, (2) shrubs, (3) herbaceous, (4) tree-shrub, (5) aquatic, (6) agricultural, and (7) other habitat (urban and barren). Within each major habitat type, multiple vegetation communities are broken down into structural classes (combining size classes with cover classes; see Figure 1 for tree habitats). For example, the tree habitats table (matrix; Table 1) has 23 tree habitats (i.e., vegetation communities dominated by trees) and each tree habitat is broken down into 17 structural stages ranging from seedlings to medium/large trees. The tree habitats have six size classes (1-6) and four cover classes (sparse, open, medium, dense) that are combined to create up to 17 unique structural classes per vegetation community (most have 16 structural types; see Table 1). Each box with a dot in its center in
Table 1 is rated by species experts using empirical studies for habitat suitability (high = 1.0, medium = 0.66, low = 0.33, and unsuitable = 0) for feeding, reproduction, and cover for each of the species in the database (Table 2). These three ratings can be combined using Equation 1 or 2, above, to evaluate an overall habitat rating (see Table 3 for an example using Equation 1). Each of the other six broad categories of major habitat types (shrubs, herbaceous, tree-shrub, aquatic, agricultural, and "other" habitat) are also broken down into structure/cover categories, though fewer than for the tree habitats, and rated for each species' suitability. Thus, each species' WHR model includes all the habitat types it uses and reflects the quality of each habitat for the species. Importantly, WHR habitats can be mapped as land cover using a GIS (see http://www.biogeog.ucsb.edu/projects/gap/gifs/vert.gif for an example map using the black-headed grosbeak). The last component of each model is a list of habitat elements either required or preferred by the species.

Table 1: Tree habitat matrix from the CWHR system and standards for tree size classes and canopy closure classes (below the matrix; from Mayer, K. E., & Laudenslayer, W. F., Jr. [Eds.] [1988]. A guide to the wildlife habitats of California. Sacramento: California Department of Forestry and Fire Protection. Copyright 1988. Reproduced by permission of the California Department of Fire and Forestry Protection.)
2.3 WHR systems and vegetation classification

An important conceptual component of WHR systems is its use of land cover maps, and in particular, vegetation classification systems. To use WHR systems effectively the pedagogy of understanding and applying classification crosswalks between databases is essential. WHR systems tend to use broadly classified vegetation communities to describe habitat types. As such these broadly defined communities usually contain many different vegetation alliances and plant associations. A "crosswalk" defines equivalent classes between tabular database systems to perform reclassification (Woolmer, 2010). Commonly, land cover datasets are mapped using different vegetation classes than a WHR system uses and therefore a crosswalk is necessary to define the WHR types from the land cover types. For example, in the CWHR system, the "valley/foothill riparian" (with the acronym "VRI") tree habitat type consists of many riparian plant community alliances and associations, such as various cottonwood and willow alliances and associations. If a land cover map is created using more floristically resolved alliances or associations, then they must be redefined (i.e. generalized) as VRI using a database crosswalk table that defines these equivalent classes. Crosswalks are implemented using a table join function in a GIS. Crosswalks are sometimes provided for commonly used land cover systems to facilitate use of the WHR system (for an example see Mayer & Laudenslayer, 1988, p. 26; Sawyer, Keeler-Wolf, & Evens, 2009).

Table 2: Selected focal species to act as a conservation umbrella for the Cache Creek Greenway near the city of Woodland. An example of student studio work (from Student Group 2015b). Colors (hue) show feeding, cover and reproductive habitats and value reflects habitat quality (darker equals higher suitability).
3 METHODS
3.1 Studio course overview and structure

Three undergraduate senior-level studio courses were taught at the University of California, Davis in the winter quarters of 2010, 2012, and 2015 (see the Acknowledgements section for student credits), examining three different river systems (each about 30 miles in length) in the Central Valley of California; to create regional greenways to connect the valley floor to the higher elevation foothill and mountain landscapes (source areas for native ungulates). The three river systems were: (1) the Stanislaus River, a west-side tributary to the San Joaquin River in the San Joaquin Valley connecting to the Sierra Nevada mountains, (2) Putah Creek, an east-side tributary to the Sacramento River in the Sacramento Valley connecting to the Coast Range mountains, and (3) Cache Creek also an east-side tributary to the Sacramento River in the Sacramento Valley connecting to the Coast Range mountains.

The design program goals of the studio projects were: (1) to facilitate seasonal migration between the valley and mountain ranges by a wide ranging ungulate, the mule deer (*Odocoileus hemionus*), (2) to provide sustainable habitat for other local wildlife and plant communities (using a coarse and fine filter approach), including special status species, such as species listed as threatened or endangered under the federal and state Endangered Species Acts, and (3) to provide recreation opportunities, including hiking trails and a regional bicycle trail. Each river is situated within a primarily agricultural landscape matrix and none currently function as a deer migration corridor, though they had historically.

### Table 3: Combined suitability values of CWHR habitat types for a suite of focal species for greenway planning and design. An example of student studio work (from Student Group 2012a).

<table>
<thead>
<tr>
<th>Species</th>
<th>Scientific Name</th>
<th>Habitat Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley Oak</td>
<td>Quercus lobata</td>
<td>Floodplain</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Giant Kudu</td>
<td><em>Tragelaphus oryx</em></td>
<td>Valley Floodplain</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td>Yellow-billed Oxpecker</td>
<td><em>Buphagus africanus</em></td>
<td>Valley Floodplain</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
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<td>M</td>
</tr>
<tr>
<td>Northern River Otter</td>
<td><em>Lontra canadensis</em></td>
<td>Valley Old Bed</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
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<td>M</td>
</tr>
<tr>
<td>Black Bear</td>
<td><em>Ursus americanus</em></td>
<td>Valley Floodplain</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
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</tr>
<tr>
<td>White-tailed Deer</td>
<td><em>Odocoileus virginianus</em></td>
<td>Valley Old Bed</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
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<tr>
<td>Red-tailed Hawk</td>
<td><em>Buteo jamaicensis</em></td>
<td>Valley Near Floodplain</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Red-winged Blackbird</td>
<td><em>Agelaius phoeniceus</em></td>
<td>Valley Old Bed</td>
<td>M</td>
<td>H</td>
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The floodplain is significantly fragmented and constrained by human land uses. Overall, the goals of the projects were to enhance and restore ecological functionality and provide limited-impact human recreation.

The main pedagogical objectives of these studio design projects were to apply the principles of WHR, landscape ecology, conservation planning, and recreation planning to real world landscapes in the
Central Valley (near UC Davis), including the cities and towns, and the surrounding agricultural landscape matrix near the rivers. The learning objectives were to:

- Examine a landscape system and ecological issues at a regional scale;
- Utilize WHR models to design functional habitat for an ecological greenway;
- Select focal species and focal habitats for planning and design (coarse and fine filter);
- Use GIS to construct a spatial database (including the use of a crosswalk);
- Design low-impact recreational facilities;
- Depict the phased implementation of the greenway.

Each student in the studio courses volunteered to participate in two teams: an information team and a design team. The information teams were divided into three topical research areas: natural systems, cultural systems, and database construction. Each design team consisted of at least one member from each information team topical area. Thus, each design team had 5-6 students with at least one representative from natural systems, one from cultural systems, and one from database construction. The information teams performed the resource inventory, some preliminary analyses, and constructed a collective database for all the design teams to utilize. Subsequently, the design teams performed additional analyses and prepared greenway alignment alternatives and selected a final alignment with phasing for their master plan.

These projects examined landscape structure and function for natural and cultural systems, however, it emphasized analysis and planning for natural systems. Each class collected a variety of information types and developed a GIS database of existing spatial data and additional data layers were developed by the students. Using these data each team of students followed a design process to: (1) conduct an inventory by summarizing important GIS layer variables, such as land use and land cover, including performing a crosswalk to WHR classes; (2) conduct a site analysis for a set of target focal species (using a multi-species umbrella approach; see section 3.2 below) in the river's region by identifying existing and potential source habitat areas, corridors, barriers, and sink habitats; (3) conduct a site analysis for public access and recreation; and (4) create a coordinated conservation greenway (or “ecological network”) master plan that incorporates the opportunities and constraints identified in the site analyses.

The studio courses were 10 weeks in length and the studio project described above was completed in the first six weeks and a second studio project followed it lasting four weeks. The second project had the students choose key nodes on their greenway alignment and they worked at a more detailed site scale to design habitat patches and recreational facilities. Typically, the second project also involved designing a multifunctional wetland (for storm water or for tertiary waste water treatment) within one of the greenway nodes. The wetland design required a topographic grading plan, planting plan, and detailed trail design that reflected design concepts to minimize conflict between people and wildlife based on the work of Cole (1993), Hellmund (1998), and Flink & Searns (1993).

### 3.2 A note on focal species and the multi-species umbrella approach

There are many approaches to selecting species for biodiversity planning (i.e., the "fine filter") including: indicator species, charismatic species, flagship species, umbrella species, focal species, vulnerable species, ecological engineers, keystone species, economically valuable species, link species, narrow endemic species, phylogenetically distinct species, and special cases (Ahern, Leduc, & York, 2006; Noon & Dale, 2002; Noss et al., 1997). Often a variety of these methods are combined for a particular conservation project.

A widely cited and popular approach is the selection of a multi-species umbrella of focal species that meet a spectrum of ecological criteria (Lambeck, 1997). In this approach Lambeck argues that a suite of focal species be selected based on key ecological limitations such that, as a whole, they protect all or most other species in the respective landscape (i.e., the umbrella effect). In this scheme species are selected based on whether a species’ needs require reconstruction of habitat (restoration) or whether a species needs land management actions to recover the population. The species that need habitat restoration are species that are area-limited, dispersal-limited, or resource-limited, while the species that need land management are typically process-limited and may require removal of exotic predators or weeds, or the addition of prescribed fire or cattle grazing.
This approach has been criticized for the assumption of nested-niches, or “nestedness,” meaning that life history requirements of multiple species cannot be assumed to entirely overlap (Lindenmayer, Manning, Smith, Possingham, Fischer, Oliver, & McCarthy, 2002). However, as Noon & Dale (2002) point out, it is impossible to monitor and assess the viability for all species at a site, especially for large regions, and therefore it is necessary to pick a subset of species for this purpose. In a response to Lindenmayer et al. (2002), a rebuttal by Lambeck (2002) states that despite the theoretical limitations of the umbrella concept, his method is the best approach because it is practical and effective, given limited funding and resources for species recovery planning and monitoring. It is important to note that the use of a WHR system can be a powerful tool to compare and group species based on their common niche requirements and identify those that do not meet the assumption of nested-niches. Cooperrider (1986) points out that WHR models can facilitate identifying guilds (i.e., groups that feed on similar food types).

For the studio course, students were instructed to use the CWHR system to select representative focal species for each of the major habitat types in the study areas including threatened or endangered species. As discussed above the students also had to include the mule deer as their wide ranging ungulate species. To determine the spatial parameters for the configuration of the seasonal migration corridor the students used a detailed spatial study mule deer migration by Sawyer, Kauffman, Nielson, & Horne (2009). The students then modeled the habitat of each species in a GIS using a land cover data set and combined all species together into a single suitability map reflecting all species (Store & Jokimaki, 2003).

4 RESULTS

The results in this paper are sample products from the student group work from the planning and design studios described above (see the Acknowledgements section for student credits). The studio products demonstrate that undergraduate students can readily understand and implement WHR models for conservation planning and greenway design projects. The CWHR models for a set of focal species representing an umbrella for a river system are shown in Table 2 and Table 3 above. A sample design process flow chart depicting a dual-track natural-cultural systems approach is shown in Figure 2.

A master plan for the Stanislaus River (2010 studio) is shown in Figure 3. The master plan depicts the final phase, configuration, and circuitry of the greenway. An example master plan from the Putah Creek greenway studio (Figure 4; 2012b) also shows the configuration, circuitry, regional bicycle trail, and greenway implementation phasing in three parts. Two example master plans are presented from the Cache Creek studio in 2015. The first example depicts a master plan and illustrates the spatial configuration and four-part implementation phasing (Figure 6). The second example also well describes the configuration, phasing and recreational facilities, including a regional bicycle trail and numerous other activities (Figure 7).

5 DISCUSSION

There is a distinct lack of discussion of the basic concepts of WHR by leaders in the field of environmental design in nearly all the major educational textbooks. This dearth of information on what WHR is and how it can be used is puzzling given its relative simplicity and its potential power as an assessment and ecological design tool. Why might this be the case? The first speculative reason for this could be its regional nature, that WHR systems are place-based, meaning the WHR models apply to vegetation communities and land cover specific to a particular geographic region. The California WHR system was first released in the late 1980s (Mayer and Laudenslayer, 1988) with its precursor publication focused on the Sierra Nevada mountains by Verner & Boss (1980). California has one of the most advanced systems in the nation, though other geographic areas also have fairly well-developed systems such as the states of Oregon and Washington (see Johnson & O'Neill, 2001). Another speculative reason for the lack of WHR discussion in the textbooks in the field of environmental design is perhaps the concept and method is too ‘new’ since the first major books on the topic were published in the mid-1980s (Verner, Morrison & Ralph, 1984) and early 1990s (Morrison, Marcot, & Mannon, 1992). The next major publication in this research realm was entitled Predicting Species Occurrences: Issues of Accuracy and Scale (Scott, Heglund, Samson, Hafler, Morrison, Raphael, & Wall, 2002). I co-authored a chapter in that book showing how a WHR model could be used to retrospectively map (postdict) habitat quality over a 60-year time period (1937-1997) using a decadal interval, for an endangered bird species and quantify the shifting habitat mosaic on a large meandering river (Greco, Plant & Barrett, 2002).
In my unsuccessful quest to find the WHR topic in educational textbooks of the environmental design field, and in the field of landscape architecture in particular, I offer a brief critique, meant as constructive criticism for improvement of future textbooks. The closest description of the WHR concept I could find in the landscape architecture educational textbook literature was in Frederick Steiner's (2000) Living Landscape (second edition) in the section describing wildlife. The description did not use the term "WHR," however, and Steiner shows a good example of how different habitats are used for "eating" (feeding), "living" (cover), and "breeding" (reproduction) for each species presented in the species-habitat matrix (see Steiner, 2000, p. 104, 106). In the classic textbook by William Marsh (2010) there is no explicit discussion of WHR models or how to use them for designing habitat for wildlife; in the section on "Vegetation as a Tool in Landscape Planning and Design" (Marsh, 2010, p. 414-419) the concept of designing wildlife habitat is entirely missing, while seven other common themes are discussed mostly relating to human landscape functionality. The case study by John Rodiek and Tom Woodfin at the end of that chapter (in Marsh, 2010, pp. 423-426) entitled Vegetation and Wildlife Habitat in Residential Planning, Central Texas also does not mention WHR, but does discuss "habitat" in non-specific terms.

Figure 2: A dual track ecological-cultural design process for greenway planning and design. An example of student studio work (from Student Group 2012b).
Figure 3: Master plan showing all phases of the ecological greenway on the Stanislaus River near the cities of Modesto, Riverbank, and Oakdale. An example of student studio work (from Student Group 2010).

Figure 4: A master plan showing each phase (color) of the ecological greenway on Putah Creek near the city of Davis. An example of student studio work (from Student Group 2012b).
Figure 5: The interrelationships between different wildlife habitat relationships for 11 focal species for the Cache Creek greenway project. An example of student studio work (from Student Group 2015a).

Figure 6: Master plan showing each phase (color) of the ecological greenway on lower Cache Creek near the city of Woodland. An example of student studio work (from Student Group 2015a).
Figure 7: Master plan showing each phase of the ecological greenway and recreational opportunities in each zone on lower Cache Creek near the city of Woodland. An example of student studio work (from Student Group 2015b).

I was unable to find any references to the concept or use of WHR in Johnson & Hill's (2002) edited text on *Ecology and Design*. In Steinitz' (2002) contribution in that volume entitled, "On Teaching Ecological Principles to Designers," it is highly recommended that WHR modeling be added as a pedagogical objective in a core curriculum. The very useful mini-textbook entitled *Landscape Ecology Principles in Landscape Architecture and Land-Use Planning* by Dramstad, Olson, & Forman (1996), as well as Forman & Godron's (1986) and Forman's (1995) landmark texts on landscape ecology, also do not explicitly discuss WHR concepts. In Peck's (1998) book on *Planning for Biodiversity*, wildlife habitat models are briefly mentioned but are not given in-depth treatment. And in terms of greenway design textbooks and articles, neither the Hellmund & Smith (2006) text nor the now out-of-print book by Flink & Searns (1993) address the concept of WHR. The final chapter in the Hellmund & Smith (2006) textbook, however, shows how species movement habitat criteria can be incorporated into the greenway design process, which is valuable.

A review of the greenway research literature similarly yielded little information about habitat design using the WHR concept and methods. The compilation of papers by Fabos & Ahern (1995) from the *Landscape and Urban Planning* journal in the book *Greenways: The Beginning of an International Movement* is an excellent resource, however, it too lacks a discussion of WHR models. A section in that book addresses "Ecological resources and nature protection in greenway planning" (Fabos & Ahern, 1995, p. 157) and contains six articles that discuss many complex planning and design processes that refer to habitat analysis, for example in Burley's (1995) study, and structure and function, such as the modified abiotic-biotic-cultural (ABC) strategy described by Mdibisi, DeMeo, and Ditto (1995), which
appear to implicitly refer to WHR attributes of habitat. Interestingly, Burley (1989) published a paper that
described the overall intent of HSI models but did not describe the underlying structure of WHR models.

In what seems somewhat paradoxical, as described above in the Introduction, there is some literature
in the environmental design field that uses WHR models in a highly advanced form. An example of this is
found in the book edited by Jongman & Pungetti (2004) entitled *Ecological Networks and Greenways:
models, again implicitly, to identify habitat for a suite of species to determine their population viability
through time using the procedure known as LARCH (Landscape ecological Analysis and Rules for the
Configuration of Habitats). Similarly, Ndubisi (2002) describes the use of the modeling systems LARCH
and LANDEP (Landscape-Ecology-and-Optimization method) that use some form of WHR models at their
core. Unfortunately, none of these articles, books, or book chapters describe the underlying WHR
concept in its basic form or how it's used. It seems an assumption is made that the reader already
understands the structure and use of WHR models and those models are then used to model habitats in
a more or less black-box form and results are presented as maps or analyses.

From the discussion above there appears to be a pedagogical need for a middle ground description
of the WHR concept and its application for habitat design for landscape architecture and environmental
planning students at the undergraduate level. I have integrated the WHR concept into the curriculum of
my undergraduate *Site Ecology* course (a combination of general ecology and site planning) and the
advanced planning and design studio course that produced the results in this paper.

It is important to note that existing WHR systems are still evolving and being refined over time and
new WHR systems are being invented for more geographic regions around the world. WHR is a
descriptive method and it is important to understand its limitations. For example, WHR models alone can
only describe species spatial distribution and not abundance (Jennings, Csuti, & Scott, 1996). More
advanced habitat evaluation systems use WHR as an input and build upon it, such as LARCH, which can
add other parameters such as home range size, or territories, to estimate carrying capacity and
population viability. The California WHR system, CWHR, is a well-developed database that describes
habitat vegetation composition, vegetative structural attributes (i.e., size and density), and habitat
elements, however, as previously noted, the CWHR system lacks specifications for habitat spatial
configurations, such as minimum patch size or corridor width. An improvement to the CWHR system
would be the addition of a fourth habitat life requisite in addition to feeding, cover, and reproduction
habitat. The fourth life requisite is 'movement habitat' and each habitat type/structural class in the system
would be rated for each species for movement suitability or as a "cost" to movement (sometimes defined
as $1 - x$ where $x$ is the habitat suitability value for a particular land cover type). An example of this
approach to model habitat connectivity to facilitate species movement was used in a study at the
Stanislaus River site near Riverbank, California (Huber, Shilling, Thorne & Greco, 2012).

6 CONCLUSION

Understanding the basic concept of WHR modeling is an important planning and design skill for
landscape architects and environmental planners. It is a tool that helps implement landscape ecological
theory and island biogeography theory. WHR has powerful applications in habitat design and
conservation planning and should not be a technique that only wildlife biologists use and conduct
research in. The theory and methods of WHR modeling are unfortunately absent, for the most-part, from
the educational textbooks in the field of landscape architecture and environmental design. In future
revisions of these textbooks the concept should be included and examples provided.

This paper demonstrates that WHR concepts can be taught to undergraduate students and the
students can design regional greenways using these and complementary methods. By using WHR
methods the resultant greenway designs are more likely to perform the ecological functions intended: to
provide feeding, cover and reproductive habitat for a selected set of focal species.

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8 REFERENCES


